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Rock mass characterization for Copenhagen Metro using face logs

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Planning and Designing Tunnels and Underground Structures

1. Summary

An extension of the existing Metro in central Copenhagen is currently under construction. We present a comparison of the different field logging techniques available from a large number of borehole logs and face logs carried out during the construction in cooperation with the constructor and client's representatives, which illustrate and approve the applied methods. The new 'Cityringen' Metro will consist of two 16 km single track tunnels, with 17 stations and 3 construction and ventilation shafts. The geological ground conditions are dominated by glacial and postglacial deposits overlying Paleocene Greensand deposits and bedrock of Paleogene 'Copenhagen limestone' characterized by alternating indurated and less indurated beds with local variations. The limestone contains layers and nodules of flint. Prior to construction works, a geological model of the Copenhagen area was set up, combining geological, geotechnical, geophysical and hydrogeological informations based on around 500 project boreholes located in close proximity to the alignment, combined with around 5000 existing boreholes in the area. Furthermore, 14 km of seismic data were included in the evaluations. Characterization and determination of relevant rock mass properties for tunnelling in Danian limestone has previously been difficult, as core logging shows a high degree of induced fracturing and core loss due to drilling disturbance, with an underestimation of the RQD values, and other rock mass properties, compared to face logging. However, describing rock mass characteristics using detailed face logging with geological description and recording of induration and fracturing, giving a field RQD value during excavation, combined with televiewer logs, when available, has shown to be a valuable tool for rock mass characterization compared to traditional classification methods only using core logs.

Keywords: *Face logging, Copenhagen 'Cityringen' Metro, Copenhagen Limestone, rock mass properties, geological modelling, field investigations*

2. Introduction

In Copenhagen a number of existing tunnels have been constructed in Danian Copenhagen Limestone, a highly anisotropic limestone comprising of alternating strongly lithified to less lithified parts. The Copenhagen Limestone, being a favourable medium for tunnelling, has proven to be difficult to characterize and determine relevant rock mass properties, resulting in previously cautious mass properties being applied. The primary investigation tool for the limestone is traditionally cored borings supplemented by geophysical investigations. During the construction of a new metro in Copenhagen, 'Cityringen', a large number of face logs have been performed during excavations of stations, shafts and caverns. At each face log the rated rock mass parameters have been characterized according to RMR method by Bieniawski (1989). This method has been found to be a valuable supplement when describing the Copenhagen Limestone, compared to traditional methods. The present contribution outlines the geological background, description methods and the results of the rock mass evaluation.

3. Geological conditions

3.1 Geological setting

The Copenhagen area is situated in the easternmost part of the Danish-Norwegian Basin, WNW-ESE trending and constricted by the Sorgenfrei-Tornquist fault zone to the north and relatively high-lying basement blocks to the south (Lund et al. 2002). The fault zone is 20-50 km wide and spreads from the North Sea in a NW-SE direction towards the Black Sea, separating crystalline basement rocks in the Scandinavian shield to the NE from a 10 km thick sedimentary succession deposited during Mesozoic. The fault was active during late Cretaceous to early Paleogene causing periods of subsidence altering with uplift in the Norwegian-Danish Basin, resulting in a number of sea level fluctuations, giving rise to periods with high sedimentation rates altering with slow sedimentation rates or erosion. 40 km west of the Sorgenfrei-Tornquist zone is the NW-SE trending Carlsberg fault, which have raised the limestone on the west side of the fault by up to 90 m. East of the fault the structural style of the limestone is dominated by gentle folding along a WNW trending axis. Several glaciers reached the area from N, NE and SE during Weichselian, eroding into the surface of the limestone and causing folding of subjacent glacial deposits, leaving some Paleocene Greensand conglomerate and sediments in the synclinals.

3.2 Lithostratigraphy and diagenesis

The bedrock in the Copenhagen area consists of Danian limestone, which is overlain by Quaternary deposits of glacial tills interbedded with meltwater deposits. Superposing Quaternary deposits are postglacial organic deposits and recent urban fill deposits. The Danian limestone is divided into bryozoan limestone of the Stevns Klint Fm, overlain by Copenhagen Limestone (København Limestone Fm) (Surlyk et al. 2006). The Copenhagen Limestone forms a 40-50 m thick unit and forms the pre-Quaternary surface east of the Carlsberg fault. The Copenhagen Limestone rests on around 50 m of bryozoan limestone, which forms the pre-Quaternary surface west of the Carlsberg fault. Bryozoan limestone has not been observed in face logs during this project and will not be discussed further. Copenhagen Limestone was deposited in a shallow marine environment and consists of a mixture of skeletal remains of planktonic organisms in a matrix of diagenetically precipitated calcite crystals. Up to 30% of the sediment consists of biogenic silica derived from silicious sponges and planktonic organisms (Knudsen et al. 1995). The diagenesis of the limestone varies from unlithified to very strongly lithified due to varying degrees of cementation and silicification. Periods of low sea water depth caused low sedimentation rate and high degree of bioturbation and lithification, whereas rapid sedimentation gave rise to less lithified sediments. The varying degree of lithification is described as induration grade H1 to H5 according to Danish practise (Larsen et al. 1995). The average density of solids of limestone is 2.66 g/cm^3 ranging from 2.5 - 2.8 g/cm^3, the varying density is caused by varying degree of contents of quartz, pyrite (FeS_2) and clay minerals, and generally increases with increasing induration degree. The bulk rock density ranges from 1.85 to 2.65 g/cm^3 and reflects porosity and grain density.

The Copenhagen Limestone contains layers and nodules of flint and silicified limestone, the flint entirely consisting of diagenetically precipitated silica, with an H5 induration, the silicified limestone consisting of a mixture of silica and carbonate, with an H4 to H5 induration. The flint is dark grey, grey or light grey in colour, while the silicified limestone is almost always light grey, and is only found in the lower unit of the Copenhagen Limestone.

Table 1 *Induration and strength-/deformation properties for Copenhagen Limestone (Kryger-Hansen & Foged, 2002)*

Degree of induration	**Description**	**ISRM rock grade**	**Unconfined compressive strength σ_c (MPa)**	**Modulus of elasticity $E_t(50)$ (MPa)**	**Tensile strength (MPa)**
H1	Unindurated Material can be formed by hand	R0	0,25-1	(130)	(≈0)
H2	Slightly indurated Material easily cut with knife	R1	1-5	1000-5000	0,2-0,8
H3	Indurated Material can be cut with knife but cannot be scratched with a fingernail	R2	5-25	5000-20000	1-4
H4	Strongly indurated Material can be scratched with knife	R3/R4	25-100	20000-60000	4-10
H5	Very strongly indurated Material cannot be scratched with knife	R5/R6	100-500	-	-

The Copenhagen Limestone is subdivided into three units (Stenestad, 1976). The Lower Copenhagen Limestone (LCL) is regularly bedded and relatively rich in clay. It is described as marly beds dark schlieren-laminated mainly caused by a high content of pyrite and glauconite (Knudsen et al. 1995). A content of intraclasts indicates that some reworking of the limestone took place before deposition of the overlying limestone. Flint is observed as dark nodules in parallel bands or irregular flint nodules. The thickness of the LCL is generally between 3 to 5 m. The unit is overlying the bryozoan limestone. LCL has not been observed in face logs during this project.

The Middle Copenhagen Limestone is irregular bedded due to bioturbation and is characterized by being nodule rich with burrows being preserved as irregular light grey flint nodules. The limestone is very irregular indurated with a lower frequency of strongly indurated beds and flint bands, as compared to Lower- and Upper Copenhagen Limestone. The thickness of the unit varies between 18 to 22 m in the Copenhagen area with a maximum thickness in the eastern part of the project area, corresponding to the uplifted anticline area. The folding in the area seems to have occurred after the deposition of the middle Copenhagen Limestone unit. The Middle Copenhagen Limestone has been observed in face logging in deep excavations at Nørrebroparken (Nøp), Sønder Boulevard (Sbv) and Øster Søgade (Øsø), and in the Frederiksberg area at sites Frederiksberg (Fb) and Frederiksberg Allé (Fba) with a high lying uplifted Middle Copenhagen Limestone level. The boundary between a benched Upper Copenhagen Limestone and nodular Middle Copenhagen Limestone ('Krøllekalk') is generally clearly visible. MCL is also to be expected for face logging at Gammel Strand, Marmorkirken and Østerport.

The Upper Copenhagen Limestone, UCL is described as horizontally bedded with layers of different hardness and thickness from a few centimetres up to 1 meter. Flint occurs in beds of 0.2 to 0.4 m thickness, occasionally up to 1 m in thickness, and can sometimes be followed over long distances. Of special interest is the uppermost part of UCL, which often consists of a strongly indurated limestone layer with large rounded dark grey flint bodies, which makes the hard surface to where Quaternary glaciers and meltwater in certain areas eroded. In places the upper zone of the UCL may be glacially disturbed and is locally heavily fractured. Accordingly the thickness of the unit is mainly governed by a combination of the folding of the limestone and glacial erosion.

Selandian Greensand (Middle Paleocene) deposits are observed locally, between the Upper Copenhagen Limestone and the Quaternary deposits. The Greensand Formation comprises a basal glauconitic, conglomeratic limestone, covered by very calcareous, sand, silt and clay soils, found locally subjacent to Quaternary deposits, often in low-lying areas protected from glacial erosion. Glauconite, an iron silicate diagnostic of marine environment, provides a characteristic light green colour to the deposits. The Greensand consists mainly of carbonate- and quarts grains mixed with carbonate mud, glauconite and fossil fragments of brachiopods, sea lily stems, shark teeth etc. The colour is dark greenish grey. Sønder Boulevard, Sbv, is located in the south of the project area and is part of the reference area for the Selandian Greensand deposits.

3.3 Geological modelling

A geological model was set up for the Copenhagen area based on an extensive amount of borehole data, geophysical data and a comprehensive logstratigraphical analysis. All together the model comprises information from about 5000 boreholes, 13 km of refraction seismic data and 257 geophysical borehole logs integrated in a detailed logstratigraphical analysis. The geological model formed the basis for planning and works in the Cityringen project. The model confirmed already known data but also gave a new improved and more detailed picture of the Quaternary deposits and the limestone surface, as well as providing information for relatively geologically unknown areas of the Copenhagen area. The geological model was presented in the form of a large number of thematic maps and vertical geological profiles along the alignment.

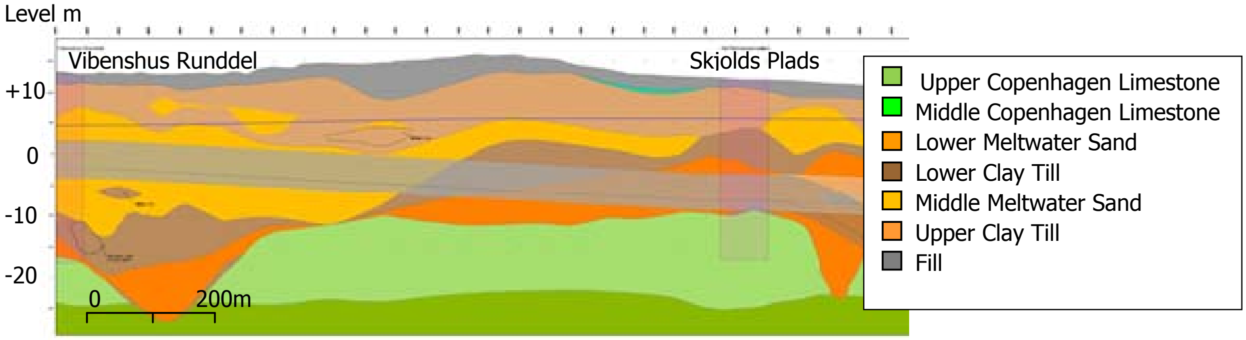

Fig. 1 *Geological cross section from north of project area, note buried valleys filled with meltwater sand, that were eroded into the limestone*

4. Field investigations

4.1 Face logging

The client (Metroselskabet I/S) performed joint supervisions and inspections with the contractor (Geo for CMT). During excavations of stations and shafts, the sites were visited for face logging and inspections 2 to 3 times per week. The excavations were face logged from below top slab to bottom of excavation, continuously through Quaternary deposits and limestone if present. Generally a face log was conducted during excavation breaks, with only limited time available, and usually one or two profiles of 2 m was logged. Quaternary deposits were described according to soil type, grain size fractions, colour and interfaces. When face logging the Copenhagen Limestone, descriptions included classification (UCL or MCL), interfaces, colour, flint content, fractures, and induration. Induration was estimated according to table 1. After each face logging an inspection report was written with face log profile, observed soil- and rock conditions, depth of excavation, progress of excavation, position of face logged profile and induration/fractures of limestone. Finally, a comparison with project investigations was made in order to evaluate if face logged soil/rock conditions were as expected.

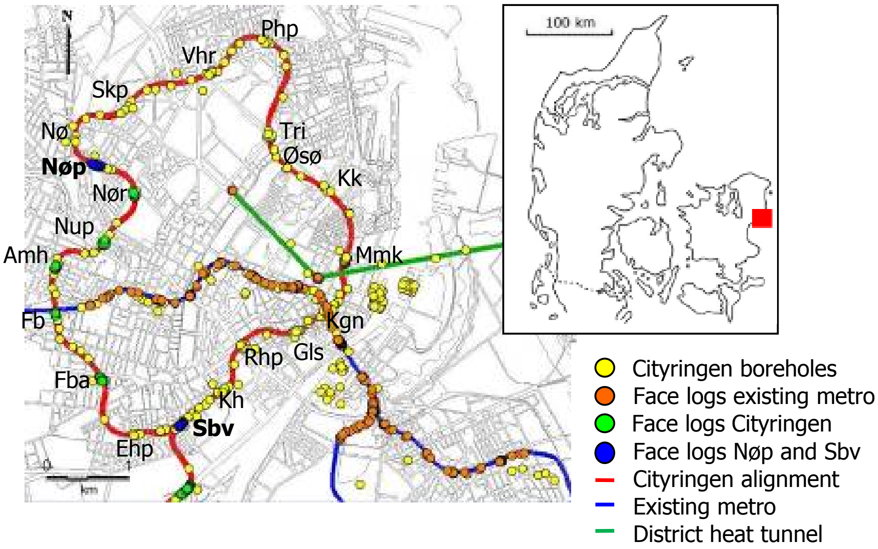

Fig. 2 *The Cityringen alignment and the existing metro. Inserted map of Denmark, red square marks the project area*

4.1.1 Rock Mass Rating

The limestone was characterized by estimating a Rock Mass Rating (RMR) value during the face logging. The characterization included estimation of strength, drill core quality, discontinuities and ground water inflow according to Bieniawski’s (1989) Rock Mass Rating system. The correlation between strength and induration is seen in table 1. The drill core quality has been substituted by the designation of RQD in the face logged profiles. RQD for face logged profiles is usually 3 to 5 times larger than RQD for borehole logs due to drilling disturbances during borehole drilling (Foged et al. 2007). It should also be noted that the ground water rating was influenced by the ground water lowering system as well as the diaphragm wall conditions. The ratings are summarized and the value defines the description class according to C. in table 2.

Table 2 *Rock Mass Rating system (modified after Bieniawski 1989)*

Parameter			**Range of values**				
1	Strength of intact rock material	Point load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	
		Uniaxial comp. strength	>250 MPa	100-250 MPa	50-100 MPa	25-50 MPa	5-25 MPa 1-5 MPa <1 MPa
	Rating		15	12	7	4	2 1 0
2	Drill core quality RQD		90-100%	75-90%	50-75%	25-50%	<25%
	Rating		20	17	13	8	3
3	Spacing of discontinuities		>2m	0.6-2m	200-600mm	60-200mm	<60mm
	Rating		20	15	10	8	5
4	Condition of discontinuities		Very rough surfaces, Not continuous, No separation, Unweathered wall rock	Slightly rough surfaces, Separation <1mm, Slightly weathered walls	Slightly rough surfaces, Separation <1mm, Highly weathered walls	Slickensided or Gouge <5mm thick or Separation 1-5mm, Continuous	Soft gouge >5mm thick or Separation >5mm, Continuous
	Rating		30	25	20	10	0
5	Groundwater	Inflow per 10m tunnel length (l/m)	None	<10	10-25	25-125	>125
		(Joint water press)/(Major principal σ	0	<0.1	0.1-0.2	0.2-0.5	>0.5
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing
	Rating		15	10	7	4	0
B. Rating adjustment for discontinuity orientations							
Strike and dip orientations			Very favourable	Favourable	Fair	Unfavourable	Very unfavourable
Ratings	**Tunnels & mines**		0	-2	-5	-10	-12
	Foundations		0	-2	-7	-15	-25
	Slopes		0	-5	-25	-50	
C. Rock mass classes determined from total ratings							
Rating			100<-81	80<-61	60<-41	40<-21	<21
Class number			I	II	III	IV	V
Description			Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

F. Effect of discontinuity strike and dip orientation in tunnelling			
Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip – Dip 45-90^o	Drive with dip – Dip 20-45^o	Dip 45-90^o	Dip 20-45^o
Very favourable	Favourable	Very unfavourable	Fair
Drive against dip – Dip 45-90^o	Drive against dip – Dip 20-45^o	Dip 0-20^o Irrespective of strike	
Fair	Unfavourable	Fair	

4.2 Site descriptions

Two sites are described in this paper, Sønder Boulevard, Sbv, and Nørrebroparken, Nøp, both deep diaphragm walled excavations reaching into Middle Copenhagen Limestone. At Nøp starting chamber caverns for the two tunnel tubes were excavated as well, one 55 m long, the other 13 m long, and both with base level around level -26 m.

4.2.1 Sønder Boulevard, Sbv

As mentioned earlier, Sbv is located in the reference area for the Paleocene Greensand Formation. At Sbv around 4 m of fossil-rich, only slightly lithified Greensand was observed below the Quaternary clay till and above the Greensand conglomerate. The Greensand conglomerate below the Greensand constitutes the boundary to the Upper Copenhagen Limestone. The boundary is well defined with a shift in colour from dark greenish grey to light grey. Just below the boundary horizontal burrows infilled with flint are observed. The top of Upper Copenhagen Limestone has been observed in 7 face log profiles, from level -7.9 to -9.3 m. The boundary between UCL and MCL was recorded in 2 profiles; at level -22.0 to -22.3 m. MCL was recorded from this level to bottom of excavation around level -32 m. The face logged limestone is dominated by induration H2 and H3, both in Upper and Middle Copenhagen Limestone.

Fig. 3 *The boundary between Selandian Greensand limestone and Danian Upper Copenhagen Limestone. Flint nodules observed just below the boundary. The nodules are infilled burrows.*

4.2.2 Nørrebroparken, Nøp

Nørrebroparken, Nøp, is located in Nørrebro in the north-west part of the project area. The shaft is around 34 m deep, excavated to level -29.5 m. Two caverns have been excavated, Track 1 is 55 m long and Track 2 is 13 m long, both with shotcrete lining. The shaft has been face logged concurrently from level +1.3 m to level -30.5 m. Quaternary deposits are observed to level -11.3 m where the limestone surface is reached. Benched Upper Copenhagen Limestone is observed from top of limestone to level -21.0 m where the boundary to Middle Copenhagen Limestone is observed. Middle Copenhagen Limestone rich in flint nodules is observed to bottom of excavation. Both caverns are excavated from around level -19 m to level -26 m with Upper Copenhagen Limestone in the top part of the cavern walls and Middle Copenhagen Limestone in the lower part of the cavern walls. The boundary between the two sub-units was often clearly defined marking a shift from benched Upper Copenhagen Limestone to nodular Middle Copenhagen Limestone. Limestone with induration H2 was dominating in the face logged profiles.

Fig. 4 *Face logged cavern wall, Track 1. The face was logged every 3 m. A lift was used for the face logging. The holes in face are due to hammering. Note shotcreted ceiling. Indurations from logged face shown to the right.*

5. Rock mass quality

5.1 Sønder Boulevard

Rock Mass Rating (RMR) was carried out in all the conducted face logs in the Greensand deposits (Greensand/Greensand conglomerate) and the Copenhagen Limestone, from level -5.5 m to level -31.9 m. The general classification parameters or ratings of RMR are listed in table 2. Mean classification parameter values for the rock conditions, evaluated from face logging at Sbv are as listed in table 3:

Table 3 *Mean classification parameter values evaluated from face logging at Sbv*

Fm	**Level /m DVR90**	**Numbers of face logs**	**Rock strength**	**RQD**	**Spacing of discontinuities**	**Conditions of discontinuities**	**Ground water**	**Orientation of discontinuities**	**RMR total**
Green-sand	-5.8 to -9.3	11	2.1±12.5	20	15-20	25	15	-5	74
UCL	-8.0 to -22.3	17	2.2±0.8	20	15-20	25	13.8	-5	73
MCL	-22.0 to -31.9	8	1.8±0.8	20	20	25	15	-5	76

The soil and rock conditions expected based on nearby boreholes, inclusive OATV logs (optical and acoustic televiewer logs) versus actual soil/rock conditions at inspection are quite consistent. However, RQD measured in face logs =90 to 100%. On the contrary drill core quality RQD in borehole logs shows mean values of 23 to 31% due to core discontinuities from drilling activity. Total core recovery (TCR) in borehole logs varies from 50 to 95% in contrast to observed fracture separations less than 1 mm in face logs and the OATV shows only very limited fracture openings in the borehole wall. RQD and TCR from core descriptions in borehole logs have been grouped for the Greensand Fm, UCL and MCL and evaluated statistically in table 4. These values have to be compared with face log RQDs of 90-100% as a documentation of the ratio of 3 to 5 (Foged et al. 2007) between RQD from core logs compared with face logs. In consequence, the combination of face log and use of RMR ratings for all 3 units lies between 61 and 80 (mean values 74, 73 and 76, see table 3) and they are thereby characterized as 'good rock'.

Table 4 *Statistical evaluation of RQD and TCR from core descriptions taken from borehole log at Sbv*

Fm	Depth (m.b.s)	Number of observations	RQD Mean±St.dev. (%)	Min	Max	TCR (%) and Core Loss ()(%)
Greensand	-8 to -9	nd	nd	nd	nd	nd
UCL	-9 to -20.5	37	31±19	0	73	82 (18)
MCL	-20.5 to -32	33	23±20	0	63	81 (19)

5.2 Nørrebroparken

Face logging with Rock Mass Rating has been carried out in the Station shaft from level -19.2 m to -29.2 m concurrently with excavation and in the Tunnel Tracks 1 and 2 excavated with shotcreting support at lengths of 55 m and 13 m, respectively. The main results from in total 43 face logs are summarized in table 5 and evaluated statistically as before for the main constructions. The corresponding RQD and TCR values collected from boreholes are listed in table 6:

Table 5 *Rock Mass Ratings for Nøp given as mean values*

Construction	Level /m DVR90	Fm	Numbers of face logs	Rock Strength	RQD	Spacing of discontinuities	Conditions of discontinuities	Ground water	Orientation of discontinuities	RMR total
Shaft	-19.2 -20,4	UCL	4	2.5	20	12.5	26.9	13.1	-2.0*	73
	-20.4 -29.2	MCL	17	1.9	20	16.8	25.4	14.9	-2.0*	74
Track 1	-19.0 -26.9	UCL/ MCL	17	1.8	20	15.6	23.1	6.6	-0.24	67
Track 2	-19.9 -26.9	UCL/ MCL	5	2.4	20	16.0	27.5	7.3	-2.6	71

Note: * evaluated based on photos and face log to be “favourable”

Table 6 *RQD and TCR values collected from boreholes at Nøp*

Fm	Depth (m.b.s.)	Number of observations n	RQD Mean±St. dev. (%)	Min	Max	TCR (%) and Core Loss () (%)
UCL	-11.2 to -20.5	21	25±17	0	43	87 (13)
MCL	-20.5 to -29.2	24	15±14	0	43	85 (15)

The rock conditions expected from the site investigations compare well to the conditions found during face logging. However, the RQD evaluated on cores in the borehole log together with the registered core loss indicate that core logging shows a high degree of induced fracturing and core loss due to drilling disturbances in respect to observations seen in the face logging during construction showing RQDs of 90 to 100%. Sample disturbance due to the drilling procedures is very important and should be taken in consideration for the rock mass rating.

6. Conclusions

An extensive number of face logs have been executed in connection with the construction of the metro project 'Cityringen' in Copenhagen. During excavation of stations, shafts and caverns concurrent face logging has been performed through Quaternary meltwater and glacial deposits and Selandian/Danian limestone, from terrain level to bottom of excavations. At each face logging rock mass parameters were evaluated resulting in a Rock Mass Rating value used for classification of the rock conditions. The mean Rock Mass Rating values estimated at the sites Sønder Boulevard and Nørrebroparken, characterize the rock conditions as 'good rock'.

The RQD evaluated at face logging is 90-100% compared to mean values of drill core quality 15-31% evaluated on cores in the borehole logs, and the Total Core Recovery (TCR) from borehole logs varies from 50 to 95% in contrast to observed fracture separations less than 1 mm in face logs and the OATV shows only very limited fracture openings in the borehole walls. The ratio of 3 to 5 between RQD from core logs compared with face logs and generally low TCR values from core logging, indicates that core logging shows a high degree of induced fracturing and core loss due to drilling disturbances which should be taken into consideration when evaluating rock mass properties in an early construction stage. The Optical and Acoustic Televiewer log OATV seems to be a useful tool to secure upscaling from cores via borehole wall features to rock mass properties.

Face logging with rock mass properties characterization according to Bieniawski's (1989) Rock Mass Rating system has been found to be a valuable tool when describing the Copenhagen Limestone for tunneling in the Copenhagen area, compared to traditional classification methods only using core logs.

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